Ultra High Energy Cosmic Rays from Cosmological Relics

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The current status of origin of Ultra High Energy Cosmic Rays (UHECR) is reviewed, with emphasis given to elementary particle solutions to UHECR problem, namely to Topological Defects and Super-Heavy Dark Matter (SHDM) particles. The relic superheavy particles are very efficiently produced at inflation. Being protected by gauge discrete symmetries, they can be long lived. They are clustering in the Galactic halo, producing thus UHECR without Greisen-Zatsepin-Kuzmin cutoff. Topological Defects can naturally produce particles with energies as observed and much higher, but in most cases fail to produce the observed fluxes. Cosmic necklaces, monopoles connected by strings and vortons are identified as most plausible sources. The latter two of them are also clustering in the halo and their observational predictions are identical to those of SHDM particles.

1. Introduction

Ultra High Energy Cosmic Rays (UHECR) is a puzzle of modern physics. Its solution needs the new ideas in astrophysics or in elementary particle physics.
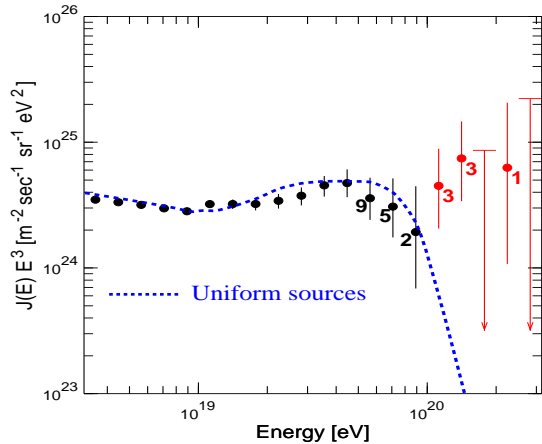

Figure 1. *AGASA spectrum compared with "astrophysical" spectrum calculated under assumptions that the sources distributed uniformly in the Universe and have generation spectrum $\sim E^{-2.3}$* [3]

The problem of UHECR is known for more than 30 years. It consits in observation of primary particles with energies up to $2 - 3 \cdot 10^{20}$ eV [1]. If these particles are extragalactic protons and their sources are distributed uniformly in the Universe, their spectrum must expose steepening, which starts at energy $E_{bb} \approx 3 \cdot 10^{19}$ eV due to interaction with microwave photons. This steepening is known as the Greisen-Zatsepin-Kuzmin (GZK) cutoff [2]. The GZK cutoff is not seen in the observed spectrum. The spectrum of UHECR according to AGASA observations [3] is shown in Fig.1 together with the spectrum calculated for uniform distribution of the sources in the Universe under assumption that generation spectrum is proportional to $E^{-2.3}$. The excess of the observed events above the GZK cutoff is clearly seen. The observational data for UHECR ($E \leq 1 \cdot 10^{19}$ eV) can be summarized as follows.

- At $E \geq 10^{19}$ eV the spectrum is flatter than at lower energies and it extends up to $2 - 3 \cdot 10^{20}$ eV (maximum observed energies).

- Chemical composition is favoured by protons, though UHE photons are not excluded as primaries.

- Data are consistent with isotropy, but close angular pairs (doublets) and triplets compose about 20% of all events at $E \geq 4 \cdot 10^{19}$ eV (22 events in doublets and triplets from 92 total [4].

Galactic origin of UHECR due to acceleration by sources located in the Galactic disc is excluded. Numerical simulations of propagation of UHECR in magnetic fields of disc and halo of the Galaxy predict the strong anisotropy for particles with rigidity $E/Z > 1 \cdot 10^{19}\ eV$ ([5] - [10]).

Extragalactic protons, if their sources are distributed uniformly in the universe, should have GZK cutoff due to pion production on microwave radiation (see Fig.1).

Extragalactic nuclei exhibit the cutoff at the same energy $E \sim 3 \cdot 10^{19}\ eV$, mainly due to e^+e^--pair production on microwave radiation [11],[5],[12].

Nearby sources must form a compact group with large overdensity of the sources to avoid GZK cutoff [5]. Local Supercluster (LS) with the typical size $R_{LS} \sim 10\ Mpc$ is a natural candidate for such group. The calculations (see [5]) show that for absence of GZK cutoff the LS overdensity $\delta_{LS} > 10$ is needed, while the observed one is $\delta_{LS} \approx 1.4$ [13]. Note, that diffusion propagation due to magnetic field cannot help in softening of GZK cutoff.

Nearby single source can provide the absence of GZK cutoff. The idea is that powerful sources of UHECR in the Universe are very rare and by chance we live nearby one of them. Such case has been numerically studied for the burst generation of UHECR and their non-stationary diffuse propagation [14]. Anisotropy can be small even at energies exceeding $1 \cdot 10^{20}\ eV$. The calculated cutoff at $E_c \approx 1 \cdot 10^{20}\ eV$ is questioned by existence of two events with energy $2 \cdot 10^{20}\ eV$.

An interesting case of single source UHECR origin was recently proposed in [15]. The physical essence of this model can be explained in the following way. A nearby single source is the powerful radio galaxy M87 in Virgo cluster. UHE particles from it falls to gigantic magnetic halo of our Galaxy (with height about 1.5 Mpc), where the azimuthal magnetic field diminishes as $1/r$. Magnetic field in the halo focuses the highest energy particles to the Sun in such way, that arriving particles have isotropical distribution. Numerical simulations of the trajectories in the magnetic field, similar to that in the galactic wind, confirm this model. This interesting proposal should be further studied taking into account such phenomena as diffuse radio, X-ray and gamma radiation produced by high energy electrons diffusing from the Galactic disc. The calculations of these processes limit the size of magnetic halo by $3-5\ kpc$ [16].

Acceleration of UHECR is a problem for astrophysical scenarios. Shock acceleration and unipolar induction are the "standard" acceleration mechanisms to UHE, considered in the literature (see [5] for a review). A comprehensive list of possible sources with shock acceleration was thoroughly studied in ref.([17]) with a conclusion, that maximum energy of acceleration does not exceed $10^{19}-10^{20}\ eV$ (see also ref.([18]) with a similar conclusion). The most promising source from this list is a hot spot in radiogalaxy produced by a jet [19–21], where maximum energy can reach $\sim 10^{20}\ eV$. Radiogalaxy M87, considered in [15], belongs to this class of sources.

Gamma Ray Bursts (GRB) models offer two new mechanisms of acceleration to UHE. The first one [22] is acceleration by ultrarelativistic shock. A reflected particle gains at one reflection the energy $E \sim \Gamma_{sh}^2 E_i$, where $\Gamma_{sh} \sim 10^2 - 10^3$ is the Lorentz factor of the shock and E_i is initial energy of a particle. The second cycle of such acceleration has extremely low probability to occur [23,24] and therefore to produce the particles with $E \sim 10^{20}\ eV$, this mechanism must operate in the space filled by pre-accelerated particles with energies $E_i > 10^{14}\ eV$.

The second mechanism [25] works in the model with multiple shocks. The collisions of the shocks produces the turbulence where the particles are accelerated by Fermi II mechanism. The turbulent velocities are mildly relativistic in the fireball rest system. The maximum energy in the rest system , $E'_{max} \sim eH'_0 l'_0$, is boosted by Lorentz factor Γ of fireball in laboratory system (here l'_0 and H'_0 are the maximum linear scale of turbulence with coherent magnetic field H'_0 there). Taking for H'_0 equipartition value, one obtains $E_{max} \sim 10^{20}\ eV$ in the laboratory system. This mechanism faces two problems. Actually the maximum energy is somewhat less than $1 \sim 10^{20}\ eV$ [26], if acceleration time is evaluated more realistically. It

diminishes the energy of GZK cutoff in the diffuse spectrum, because it is formed by the particles with production energies higher than the observed ones. The most serious problem, however, is that the produced flux of accelerated particles suffer the adiabatic energy losses [26].

In summary, the acceleration (astrophysical) scenarios are somewhat disfavoured, but not excluded. Apart from them, many elementary particle solutions were proposed to solve UHECR puzzle. Among them there is such an extreme proposal as breaking the Lorentz invariance [27], light gluino as the lightest supersymmetric particle and UHE carrier [28], UHE neutrinos producing UHECR due to resonance interaction with the dark matter neutrinos [29] and some other suggestions. In this paper I will review two most conservative sources of UHECR of non-accelerator origin: Superheavy Dark Matter (SHDM) and Topological Defects (TD).

2. UHECR from Superheavy Dark Matter

Superheavy Dark Matter (SHDM) as a source of UHECR was first suggested in refs.([30, 31]). SHDM particles with masses larger than 10^{13} GeV are accumulated in the Galactic halo [30] with overdensity $\sim 10^5$ and hence UHECR produced in their decays do not exhibit the GZK cutoff. The other observational signatures of this model are dominance of UHE photons [30] and anisotropy connected with non-central position of the Sun in the Galactic halo [32,33].

Production of SHDM
SHDM particles are very efficiently produced by the various mechanisms at post-inflationary epochs. This common feature has a natural explanation. The SHDM particles due to their tremendous mass had never been in the thermal equilibrium in the Universe and never were relativistic. Their mass density diminished as $\sim 1/a^3$, while for all other particles it diminishes much faster as $\sim 1/a^4$, where a is the scaling factor of the Universe. When normalized at inflationary epoch, $a_i = 1$, $a(t)$ reaches enormous value at large t. It is enough to produce negligible amount of superheavy particles in the post-inflationary

epoch in order to provide $\Omega_X \sim 1$ now. Actually, in most cases one meets a problem of overproduction of SHDM particles (further on we shall refer to them as to X-particles).

One very general mechanism of X-particle production is given by creation of particles in time-variable classical field. In our case it can be inflaton field ϕ or gravitational field. In case of inflaton field the direct coupling of X-particle (or some intermediate particle χ) with inflaton is needed, *e.g.* $g^2\phi^2X^2$ or $g^2\phi^2\chi^2$. The intermediate particle χ then decays to X-particle. In case of time-variable gravitational field no coupling of X to inflaton or any other particles is needed: X-particles are produced due to their masses. For the review of above-mentioned mechanisms and references see [34].

Super-heavy particles are very efficiently produced at *preheating* [35]. This stage, predecessor of *reheating*, is caused by oscillation of inflaton field after inflation near the minimum of the potential. Such oscillating field can nonperturbatively (in the regime of broad parametric resonance) produce the intermediate bosons χ, which then decay to X-particles. The mass of X-particles can be one-two orders of magnitude larger than inflaton mass m_ϕ, which should be about 10^{13} GeV to provide the amplitude of density fluctuations observed by COBE.

Another mechanism, more efficient than parametric resonance and operating in its absence, is so-called *instant preheating* [36]. It works in the specific models, where mass of χ particles is proportional to inflaton field, $m_\chi = g\phi$. When inflaton goes through minimum of potential $\phi = 0$ χ-particles are massless and they are very efficiently produced. When $|\phi|$ increases, m_χ increases too and can reach the value close to m_{Pl}.

Another possible mechanisms of SHDM particle production are non-equilibrium thermal production at reheating and by early topological defects [30]. The latter can be produced at reheating [35].

Gravitational production of particles occurs due to time variation of gravitational field during expansion of the universe [37]. For particles with the conformal coupling with gravity, $(1/6)RX$, where R is the space-time curvature of the ex-

panding universe, the particle mass itself couples a particle with the field (gravitation) and any other couplings are not needed. X particles can be even sterile! Neither inflation is needed for this production. It rather limits the gravitational production of the particles. Since this production is described by time variation of the Hubble constant $H(t)$, only particles with masses $m_X \leq H(t)$ can be produced. In inflationary scenario $H(t) \leq m_\phi$, where m_ϕ is the mass of the inflaton. It results in the limit on mass of produced particles $m_X \leq 10^{13}$ GeV [38,39].

The gravitational production of superheavy particles was recently studied in refs[38,39] (see [34] for a review). It is remarkable that for the mass $m_X \sim 10^{13}$ GeV the relic density is $\Omega_X \sim 1$ without any additional assumptions. It makes superheavy particles most natural candidates for Cold DM.

Lifetime
Superheavy particles are expected to be very short-lived. Even gravitational interaction (e.g. described by dimension 5 operators suppressed by the Planck mass) results in the lifetime much shorter than the age of the Universe t_0. The superheavy particles must be protected from fast decay by some symmetry, respected even by gravitational interaction, and such symmetries are known. They are discrete gauge symmetries. They can be very weakly broken e.g. by wormhole effects [30] or instanton effects [31] to provide the needed lifetime. The systematic analysis of broken discrete gauge symmetries is given in ref.[40]. For the group Z_{10} the lifetime of X-particle with $m_X \sim 10^{13} - 10^{14}$ GeV was found in the range $10^{11} - 10^{26}$ yr. The realistic elementary particle models for such long-lived particles were suggested [41,42].

Spectrum of UHECR
Quark and gluons produced in the decay of superheavy particle originate QCD cascade, similar to that from Z^0 decay. The resulting spectrum of hadrons can be calculated using the standard QCD technique [43,44]. The spectrum of hadrons is not power-law, its most spectacular feature is the Gaussian peak at small x. Photons dominate the primary spectrum by a factor ~ 6. The calcu-

lations of the spectrum were performed in ref.[46] (HERWIG MC simulation for ordinary QCD) and in ref.[45] (analytic MLLA calculations for SUSY QCD).

Observational predictions.
Overdensity δ of SHDM particles in the Galactic halo is the same as for any other form of CDM, and numerically it is given by a ratio of CDM density observed in the halo to CDM density in extragalactic space ($\delta \sim 10^5$).

Spectrum of UHECR produced by decaying X-particles in the Galactic halo and beyond is shown in Fig.2. One can see that UHE photon flux appreciably dominates over that of protons.
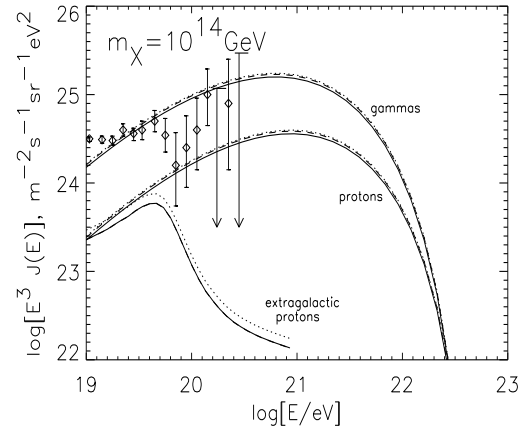

Figure 2. *Predicted fluxes of UHE photons and protons from the decay of superheavy relic particles with mass $m_X = 1 \cdot 10^{14}$ GeV. [33]. The solid, dotted and dashed curves correspond to different distributions of SHDM in the halo. Observational data are from AGASA.*

Anisotropy is caused by non-central position of the Sun in the halo. Most notable effect, the difference in fluxes in directions of Galactic center and anticenter, cannot be observed by existing arrays. Calculated phase and amplitude of the first harmonic of anisotropy [47,48] are compared in Fig.3 with observations. In spite of the visual agreement, one might only conclude that predicted anisotropy does not contradict the observations: within 1.5σ AGASA data are compatible with isotropy.
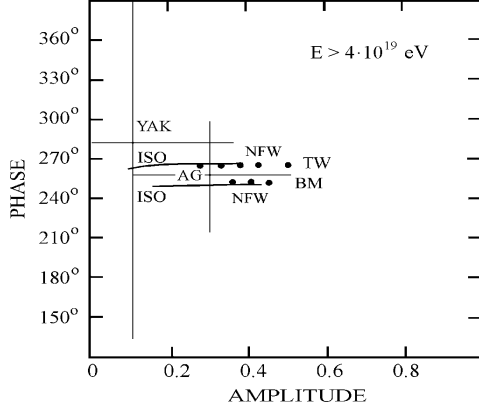
Figure 3. *Amplitude and phase of the first harmonic of anisotropy for the AGASA (AG) and Yakutsk (YAK) arrays. Solid lines are for ISO distribution of DM and dots (NFW) for NFW numerical simulations [49]. BM [47] and TW [48] calculations agree with each other.*

Angular clustering in UHECR arrival (doublet and triplet events) can be due to clumpiness of DM halo. Numerical N-body simulations show the presence of dense DM clouds in the halo. For example, the high resolution simulations of ref.[50] predict about 500 DM clouds with masses $M \sim 10^8 M_\odot$ in the halo of our Galaxy. The baryonic content of these clouds should be low [51], and therefore one cannot expect the identification of *all sources* of UHECR doublets and triplets with the observed clouds. The smallest clumps resolved so far in the high resolution simulations reach $M_{cl} \sim 10^6 M_\odot$, *i.e.* they fall into range of the globular cluster masses. It could be that some of the doublet/triplet UHECR sources are globular clusters.

The high resolution simulations demonstrate the early origin of the clumps ($z \approx 5$) [50], and therefore the core overdensity, as compared with present density, is $(1+z)^3 \sim 200$. The extended halos of DM clouds can be stripped away by tidal interactions when clouds cross the galactic disc. The formation of dense compact DM objects was discussed in refs.[52,53].

Assuming the typical distance of a dense compact cloud to the sun as $r \sim 1\ kpc$, one can

estimate the fraction of UHE particles arriving to us from one of these objects as $f \sim (M_{cl}/M_h)(R_h^2/r^2)$, where $R_h \sim 100\ kpc$ is a size of the halo, and M_{cl} and M_h are the masses of a cluster and halo, respectively. For $M_{cl} \sim 10^6 M_\odot$, $M_h \sim 10^{12} M_\odot$ and $r \sim 1\ kpc$, one obtains $f \sim 0.01$, *i.e.* about ten of such sources can provide the doublets and triplets observed in AGASA and other detectors. Part of these sources can be globular clusters.

More detailed discussion will be presented in one of forthcoming publications by A.Vilenkin and the author.

3. Topological defects.

Topological defects, TD, (for a review see [54]) can naturally produce particles of ultrahigh energies (UHE). The pioneering observation of this possibility was made by Hill, Schramm and Walker [55] (for a general analysis of TD as UHE CR sources see [56]).

In many cases TD become unstable and decompose to constituent fields, superheavy gauge and Higgs bosons (X-particles), which then decay producing UHECR. It could happen, for example, when two segments of ordinary string, or monopole and antimonopole touch each other, when electrical current in superconducting string reaches the critical value and in some other cases.

In most cases the problem with UHECR from TD is not the maximal energy, but the fluxes. One very general reason for the low fluxes consists in the large distance between TD. A dimension scale for this distance is the Hubble distance H_0^{-1}. However, in some rather exceptional cases this dimensional scale is multiplied to a small dimensionless value r. If a distance between TD is larger than UHE proton attenuation length, then the flux at UHE is typically exponentially suppressed.

The following TD have been discussed as potential sources of UHE particles: superconducting strings [55], ordinary strings [57], [58],[59], magnetic monopoles , or more precisely bound monopole-antimonopole pairs (monopolonium [60,61] and monopole-antimonopole connected by strings [62]), networks of monopoles

connected by strings [63], necklaces [64], and vortons [65].

Monopolonia, monopole-antimonopole connected by strings and vortons are clustering in Galactic halo [33] and their observational signatures for UHECR are identical to SHDM particles discussed above.

(i) *Superconducting strings.*
As was first noted by Witten[66], in a wide class of elementary particle models, strings behave like superconducting wires. Moving through cosmic magnetic fields, such strings develop electric currents. Superconducting strings produce X particles when the electric current in the strings reaches the critical value. Superconducting strings produce too small flux of UHE particles [33] and thus they are disfavoured as sources of observed UHECR.

(ii) *Ordinary strings.*
There are several mechanisms by which ordinary strings can produce UHE particles.

For a special choice of initial conditions, an ordinary loop can collapse to a double line, releasing its total energy in the form of X-particles[57]. However, the probability of this mode of collapse is extremely small, and its contribution to the overall flux of UHE particles is negligible.

String loops can also produce X-particles when they self-intersect (e.g. [67]). Each intersection, however, gives only a few particles, and the corresponding flux is very small [68].

Superheavy particles with large Lorentz factors can be produced in the annihilation of cusps, when the two cusp segments overlap [69]. The energy released in a single cusp event can be quite large, but again, the resulting flux of UHE particles is too small to account for the observations [70,68].

It has been recently argued [58] that long strings lose most of their energy not by production of closed loops, as it is generally believed, but by direct emission of heavy X-particles. If correct, this claim will change dramatically the standard picture of string evolution. It has been also suggested that the decay products of particles produced in this way can explain the observed flux of UHECR [58]. However, as it is argued in ref [33], numerical simulations described in [58]

allow an alternative interpretation not connected with UHE particle production.

But even if the conclusions of [58] were correct, the particle production mechanism suggested in that paper cannot explain the observed flux of UHE particles. If particles are emitted directly from long strings, then the distance between UHE particle sources D is of the order of the Hubble distance H_0^{-1}, $D \sim H_0^{-1} \gg R_p$, where R_p is the proton attenuation length in the microwave background radiation. In this case UHECR flux has an exponential cutoff at energy $E \sim 3 \cdot 10^{10}\ GeV$. In the case of accidental proximity of a string to the observer, the flux is strongly anisotropic. A fine-tuning in the position of the observer is needed to reconcile both requirements.

(iii) *Monopolonium and $M\bar{M}$-pair connected by string.*
Monopole-antimonopole pairs $(M\bar{M})$ can form bound state [60]. Spiraling along the classical orbits they fall to each other and annihilate, producing superheavy particles. The lifetime of this system depends on the initial (classical) radius, and can be larger than the age of the Universe t_0 [60]. Production of UHECR by monopolonia was studied in ref.[61] (clustering of monopolonia in the Galactic halo was not noticed in this paper and was indicated later in ref.[33]).

Recently [62] it was demonstrated that friction of monopoles in the cosmic plasma results in the monopolonium lifetime much shorter than t_0. Instead of monopolonium the authors have suggested a similar object, $M\bar{M}$ pair connected by a string, as a candidate for UHECR. This TD is produced in the sequence of the symmetry breaking $G \rightarrow H \times U(1) \rightarrow H$. At the first symmetry breaking monopoles are produced, at the second one each $M\bar{M}$-pair is connected by a string. For the light strings the lifetime of this TD is larger than t_0. $M\bar{M}$-pairs connected by strings are accumulated in the halo as CDM and have the same observational signatures as SHDM particles.

(iv)*Network of monopoles connected by strings.*
The sequence of phase transitions

$$G \rightarrow H \times U(1) \rightarrow H \times Z_N \qquad (1)$$

results in the formation of monopole-string networks in which each monopole is attached to N

strings. Most of the monopoles and most of the strings belong to one infinite network. The evolution of networks is expected to be scale-invariant with a characteristic distance between monopoles $d = \kappa t$, where t is the age of Universe and $\kappa = const$. The production of UHE particles are considered in [63]. Each string attached to a monopole pulls it with a force equal to the string tension, $\mu \sim \eta_s^2$, where η_s is the symmetry breaking vev of strings. Then monopoles have a typical acceleration $a \sim \mu/m$, energy $E \sim \mu d$ and Lorentz factor $\Gamma_m \sim \mu d/m$, where m is the mass of the monopole. Monopole moving with acceleration can, in principle, radiate gauge quanta, such as photons, gluons and weak gauge bosons, if the mass of gauge quantum (or the virtuality Q^2 in the case of gluon) is smaller than the monopole acceleration. The typical energy of radiated quanta in this case is $\epsilon \sim \Gamma_M a$. This energy can be much higher than what is observed in UHECR. However, the produced flux (see [33]) is much smaller than the observed one.

(v) *Vortons.*
Vortons are charge and current carrying loops of superconducting string stabilized by their angular momentum [71]. Although classically stable, vortons decay by gradually losing charge carriers through quantum tunneling. Their lifetime, however, can be greater than the present age of the universe, in which case the escaping X-particles will produce a flux of cosmic rays. The X-particle mass is set by the symmetry breaking scale η_X of string superconductivity.

The number density of vortons formed in the early universe is rather uncertain. According to the analysis in ref.[72], vortons are overproduced in models with $\eta_X > 10^9 GeV$, so all such models have to be ruled out. In that case, vortons cannot contribute to the flux of UHECR. However, an alternative analysis [71] suggests that the excluded range is $10^9 GeV < \eta_X < 10^{12} GeV$, while for $\eta_X \gg 10^{12} GeV$ vorton formation is strongly suppressed. This allows a window for potentially interesting vorton densities with $\eta_X \sim 10^{12} - 10^{13} GeV$. Production of Ultra High Energy particles by decaying vortons was studied in ref.[65].

Like monopoles connected by strings and SH

relic particles, vortons are clustering in the Galactic halo and UHECR production and spectra are identical in these three cases.

(vi) *Necklaces.*
Necklaces are hybrid TD corresponding to the case $N = 2$ in Eq.(1), i.e. to the case when each monopole is attached to two strings. This system resembles "ordinary" cosmic strings, except the strings look like necklaces with monopoles playing the role of beads. The evolution of necklaces depends strongly on the parameter

$$r = m/\mu d, \qquad (2)$$

where d is the average separation between monopoles and antimonopoles along the strings. As it is argued in ref. [64], necklaces might evolve to configurations with $r \gg 1$, though numerical simulations are needed to confirm this conclusion. Monopoles and antimonopoles trapped in the necklaces inevitably annihilate in the end, producing first the heavy Higgs and gauge bosons (X-particles) and then hadrons. The rate of X-particle production can be estimated as [64]

$$\dot{n}_X \sim \frac{r^2 \mu}{t^3 m_X}. \qquad (3)$$

Restriction due to e-m cascade radiation demands the cascade energy density $\omega_{cas} \leq 2 \cdot 10^{-6} \ eV/cm^3$. The cascade energy density produced by necklaces can be calculated as

$$\omega_{cas} = \frac{1}{2} f_\pi r^2 \mu \int_0^{t_0} \frac{dt}{t^3} \frac{1}{(1+z)^4} = \frac{3}{4} f_\pi r^2 \frac{\mu}{t_0^2}, \quad (4)$$

where $f_\pi \approx 0.5$ is a fraction of total energy release transferred to the cascade. The separation between necklaces is given by [64] $D \sim r^{-1/2} t_0$ for large r. Since $r^2 \mu$ is limited by cascade radiation, Eq.(4), one can obtain a lower limit on the separation D between necklaces as

$$D \sim \left(\frac{3 f_\pi \mu}{4 t_0^2 \omega_{cas}} \right)^{1/4} t_0 > 10 (\mu/10^6 \ GeV^2)^{1/4} \ kpc, (5)$$

Thus, necklaces can give a realistic example of the case when separation between sources is small and the Universe can be assumed uniformly filled by the sources.

The fluxes of UHE protons and photons are shown in Fig.4 according to calculations of

ref.[33]. Due to absorption of UHE photons the proton-induced EAS from necklaces strongly dominate over those induced by photons at all energies except $E > 3 \cdot 10^{11}$ GeV, where photon-induced showers can comprise an appreciable fraction of the total rate.
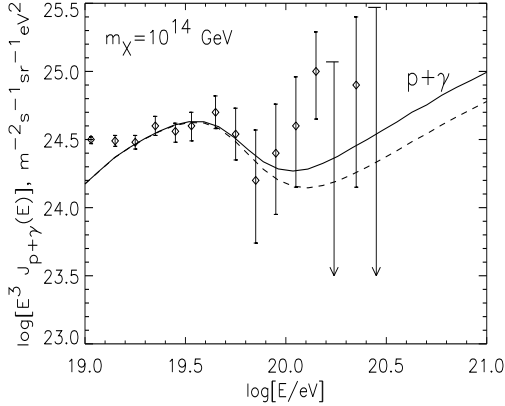

Figure 4. *Spectrum of UHE photons + protons from necklaces compared with AGASA measurements. Solid and dashed curves correspond to different absorption of UHE photons in extragalactic space.*

4. Conclusions

At $E \geq 1 \cdot 10^{19}$ eV a new component of cosmic rays with a flat spectrum is observed. According to the Fly's Eye and Yakutsk data the chemical composition is better described by protons than heavy nuclei. The AGASA data are consistent with isotropy in arrival of the particles, but about 20% of particles at $E \geq 4 \cdot 10^{19}$ eV arrive as doublets and triplets within $\sim 2 - 4°$.

The galactic origin of UHECR due to conventional sources is disfavoured: the maximal observed energies are higher than that calculated for the galactic sources, and the strong Galactic disc anisotropy is predicted even for the extreme magnetic fields in the disc and halo.

The signature of extragalactic UHECR is GZK cutoff. The position of steepening is model-dependent value. For the Universe uniformly filled with sources, the steepening starts at $E_{bb} \approx 3 \cdot 10^{19}$ eV and has $E_{1/2} \approx 6 \cdot 10^{19}$ eV (the energy at which spectrum becomes a factor of two lower

than a power-law extrapolation from lower energies). The spectra of UHE nuclei exhibit steepening approximately at the same energy as protons. UHE photons have small absorption length due to interaction with radio background radiation.

The extragalactic astrophysical sources theoretically studied so far, have either too small E_{max} or are located too far away. The Local Supercluster (LS) model can give spectrum with $E_{1/2} \sim 10^{20}$ eV, if overdensity of the sources is larger than 10. However, IRAS galaxy counts give overdensity $\delta = 1.4$.

GRBs and a nearby single source (*e.g.* M87) remain the potential candidates for the observed UHECR.

Superheavy Dark Matter can be the source of observed UHECR. These objects can be relic superheavy particles or topological defects such as $M\bar{M}$-pairs connected by strings or vortons. These objects are accumulated in the halo and thus the resulting spectrum of UHECR does not have the GZK cutoff. In this case UHECR is a signal from inflationary epoch, because both superheavy particles and topological defects are most probably produced during reheating.

The observational signatures of UHECR from SHDM are (i) absence of GZK cutoff, (ii) UHE photons as the primaries and (iii) anisotropy due to non-central position of the Sun in the halo. The angular clustering is possible due to clumpiness of DM in the halo.

Topological Defects naturally produce particles with extremely high energies, much in excess of what is presently observed. However, the fluxes from most known TD are too small. Only necklaces, $M\bar{M}$ connected by strings and vortons remain candidates for the sources of the observed UHECR. Necklaces give so far the only known example of extragalactic TD as a sources of UHECR. Its signature is the presence of the photon component in the primary radiation and its dominance at the highest energies $E > 10^{20}$ eV.

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